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ACTIVITIES TO IMPROVE WSR-88D RADAR RAINFALL ESTIMATION IN THE NATIONAL WEATHER SERVICE

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INTRODUCTION

The National Weather Service (NWS) began the installation across the U.S. of its next generation of operational Doppler weather radars, NEXRAD, about ten years ago. The resulting 160 radars, called WSR-88D (Weather Surveillance Radar-1988 Doppler), have revolutionized the NWS forecast and warning program through improved detection of severe wind, hail, and tornadoes and also for improved hydrologic forecast operations and services. This paper provides an overview of the WSR-88D precipitation algorithms and products and discusses our current development and implementation plans for enhancing them. This plan is driven by the desire to improve our hydrologic operations and services to the Nation and to facilitate productive use of the WSR-88D radar network for real-time hydrologic modeling activities in the NWS and its partners.

OVERVIEW OF PRECIPITATION PROCESSING AND PRODUCTS

Design Framework

There are many value-added processing algorithms that run on the WSR-88D computer system to produce derived products from the raw radar data for use by NWS forecasters and customers outside of the NWS (Klazura and Imy 1993). The Precipitation Processing System (PPS) is the first of two hydrologic algorithms that computes initial gridded precipitation estimates within the WSR-88D radar system at each Weather Forecast Office (WFO) (Fulton et al. 1998). It has been undergoing enhancements over the years to improve the quantitative reliability of the rainfall estimates. Additional value-added processing of these PPS rainfall products is currently performed outside of the WSR-88D radar system within the NWS's Advanced Weather Interactive Processing System (AWIPS) at each of 13 River Forecast Centers (RFC) across the U.S and, by this fall, at each of 120 WFOs (see http://www.srh.noaa.gov/default.html for forecast office web links). Within the follow-on AWIPS Multisensor Precipitation Estimator (MPE), the raw single-radar-site PPS rainfall products from adjacent radars are passed to each regional RFC where rain gauge and satellite data are merged with the PPS rainfall products to produce a variety of regionally-mosaicked, raingauge-calibrated multisensor rainfall products as input into operational hydrologic models for river forecast and flood warning purposes and for distribution to external customers.

The original design framework for NEXRAD precipitation processing algorithms was driven by several fundamental requirements that are still valid today:

• *State-of-the-art science* using the latest scientific techniques to convert radar measurements into precipitation accumulations.

• *Utilization of all available independent rainfall sensors* such as rain gauges and satellite-based precipitation estimates in combination with the radar estimates to maximize the quantitative integrity of the final products and to minimize any bias errors that may be inherent in any single-sensor estimator.

• *Integrated end-to-end processing within existing NWS computer processing and data systems*. Preliminary precipitation processing on the WSR-88D system must be integrated end-to-end with follow-on, value-added precipitation processing algorithms within the NWS's external AWIPS computers, including integration with operational hydrologic forecasting algorithms at the River Forecast Centers.

• *Software and dataflow efficiency*. The numerous WSR-88D scientific processing algorithms must be computationally efficient in order to smartly reduce the large volume of raw radar data into smaller, manageable, derived products at the source radar that can be efficiently transmitted to external users and AWIPS over available transmission lines to reduce data communication loading.

• *Operational robustness and fail-safe reliability*. Since the radar operates 24 hours a day, 7 days a week, the software algorithms must necessarily be robust, immune to software failure, and reliable under all possible conditions.

• *Extensibility, flexibility, and tunability*. Because the U.S. contains a wide variety of weather and climate regimes ranging from the warm, dry climate of the Desert Southwest to the tropical environment along the Gulf Coast to the cold climate of the Northern Plains, the precipitation algorithms must be designed to permit flexibility and tuning of the scientific techniques to the local climate conditions where the algorithms are running. In order to satisfy this requirement, the PPS and MPE algorithms contain user-selectable parameters that allow the forecasters to adapt the algorithms to local conditions for optimized precipitation product generation. Our ultimate goal of developing adaptive techniques that automatically adjust the parameters to the local conditions using past verification statistics and current weather observations has yet to be realized.

Computer, information, and communication technology have advanced significantly since the early days of the WSR-88D radar and have made several of these requirements easier to achieve today even though our appetites inevitably grow in step with available technology advancement. As such, much of the original 1980's-era radar computing hardware and software, which was state-of-the-art at the time, is now currently being replaced at all radar sites with advanced extensible state-of-the-art radar, computer, and communication technology to alleviate original technology limitations, to permit the radar system to increase processing power, and to utilize off-the-shelf “open systems” computer components instead of the previous customized components to reduce long-term maintenance costs (Saffle et al. 2002). Additional improvements have been implemented in the software engineering process that will speed the implementation of new scientific enhancements into the system. The Open Systems WSR-88D radar network is the most advanced operational weather radar system in the world today and will serve as the host to even more significant technology deployments in the near future, including advanced digital signal processing and dual polarization hardware, that will result in improved rainfall estimation capabilities for hydrologic applications.

Precipitation Processing System

The Precipitation Processing System (PPS) is the first of two serial processing algorithms that computes precipitation estimates. It runs at each of the 160 WSR-88D radars and automatically computes precipitation estimates on a polar grid out to a maximum range of 230 km from the radar using as input the raw reflectivity factor measurements collected by the radar. Details of the scientific processing steps are described in Fulton et al. (1998). Very briefly, reflectivity factor measured by the radar, which is generally proportional to rainfall intensity, is converted to rainrate using one of several common empirical power-law equations. Then rainrate is integrated over time to produce estimated rainfall depth. The rainfall grid is a fixed 1-degree in azimuth by 2-km in range, and therefore grid cells range in size from about 1 km^2 at close ranges to 8 km^2 at far ranges. The rainfall accumulations, with internal precision of 0.1 mm of rainfall, are updated every 5-10 minutes depending on which of several scanning modes the radar is operating in. Thus the WSR-88D provides high resolution rainfall estimates in time and space suitable for distributed hydrologic modeling of small catchments.

The PPS currently generates four rainfall products updated every 5-10 minutes: the One-Hour Precipitation accumulation product (OHP), the Three-Hour Precipitation accumulation product (THP), the Storm-Total Precipitation accumulation product (STP), and the Hourly Digital Precipitation Array (DPA) product. The first three products are graphical products of rainfall depth in inches that has been quantized into 16 rainfall data levels. The graphical OHP and STP image products, and time loops of these products, can be accessed in real-time via the world wide web at http://weather.noaa.gov/radar/mosaic/DS.p19r0/ar.us.conus.shtml by clicking on any region on the U.S. map to bring up the local radar images. An example of an STP product is shown in Figure 1.

The fourth precipitation product is the DPA. This is currently the only rainfall product produced by the PPS that is suitable for follow-on quantitative applications such as hydrologic modeling because it has a full 256 data levels in units of logarithm of rainfall depth, unlike the quantized 16-data-levels in the graphical products above. It is a running one-hour rainfall accumulation product, updated every 5-10 minutes, on a national polar stereographic grid called the NWS HRAP (Hydrologic Rainfall Analysis Project) grid that is nominally 4-km on a side in midlatitudes. This DPA product and HRAP grid are described in Fulton (1998) and Reed and Maidment (1999). Instructions for using the HRAP grid within commercial GIS packages are described at http://www.nws.noaa.gov/oh/hrl/distmodel/hrap.htm. Real-time FTP access to these and all WSR-88D products from all conterminous radars can be obtained by following instructions at http://205.156.54.206/oso/rpccds.html.

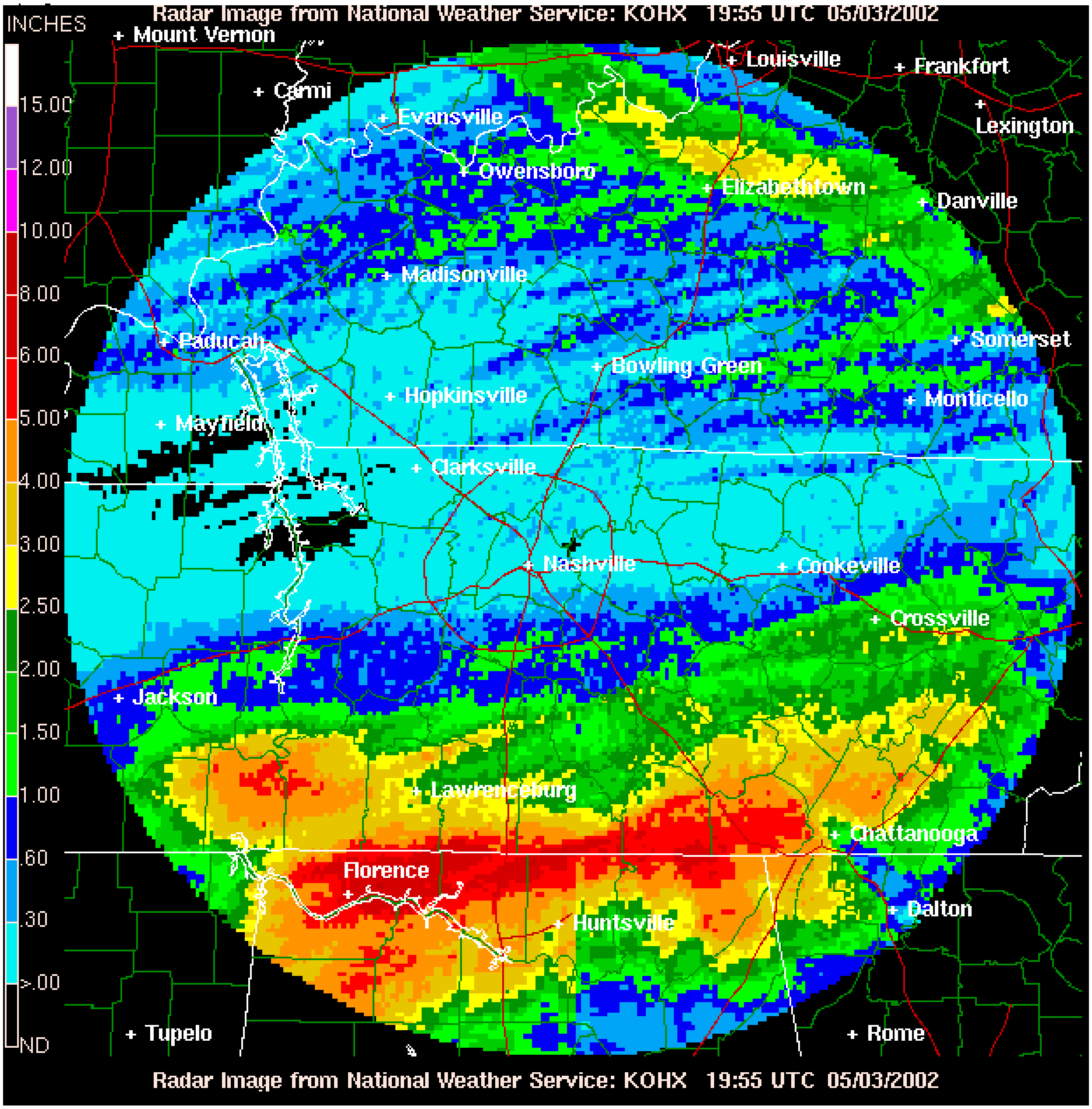

Figure 1. Example of a 16-level graphical PPS Storm-Total Precipitation (STP) product from the Nashville, TN WSR-88D radar. The maximum range shown is 230 km.

A new digital rainfall accumulation product, called the Digital Storm-total Precipitation (DSP) product, will be generated beginning in the spring of 2003 at all WSR-88D radars. This product is fundamentally a digital (i.e., full 256 data levels) representation of the existing graphical STP product, but it will be on the national 1-km by 1-km HRAP grid instead of the polar grid. This will permit easy mosaicking of products from adjacent radars and save users the trouble of remapping from a polar to a Cartesian grid. It will be updated every 5-10 minutes and contain gridded rainfall accumulations summed up since the last one-hour rain-free period. The advantage of this product over the existing DPA is that any arbitrary accumulation duration can be generated from consecutive DSPs by simple differencing. This is not easily doable with the DPA products because they are running one-hour accumulations. This product will be used within the Multisensor Precipitation Estimator at the WFOs in the future in order to generate high resolution rainfall products suitable for use in distributed hydrologic models and flash flood monitoring and forecasting tools.

Multisensor Precipitation Estimator

The Multisensor Precipitation Estimator (MPE) algorithm is the second and final rainfall processing algorithm that builds upon the previous PPS processing. The PPS rainfall products are only first-guess rainfall products because they are based on radar data alone which has known biases. Important follow-on, value-added processing is performed afterwards in MPE using these PPS products as initial estimates in combination with independent rain gauge and satellite rainfall information. Even though PPS products are easily accessible to customers via the internet, they should be used with the understanding that quantitatively more-reliable MPE multisensor rainfall products are generated and distributed routinely by the NWS to external customers that are quantitatively better than the radar-only PPS products.

The MPE algorithm currently runs interactively once an hour within AWIPS at the 13 River Forecast Centers to support operational hydrologic forecasting and warning, but it will also be running at the Weather Forecast Offices beginning in the fall of 2002 to support flash flood monitoring and warning. MPE uses as input the hourly DPA products from the PPS at each WSR-88D, but it adds significant value to the individual PPS radar-only products by 1) mosaicking DPA products from adjacent regional radars to create larger regional gridded hourly rainfall maps, 2) quantitatively incorporating real-time rain gauge data to calibrate the radar rainfall estimates and reduce biases, 3) incorporating satellite-based rainfall estimates to add additional rainfall information to the radar and rain gauge rainfall estimates, and 4) permitting manual forecaster interaction, editing, and quality control of the input data and products. A description of MPE can be found in an on-line NWS forecaster training course at http://www.nws.noaa.gov/oh/hrl/presentations/mpe_training_wkshp_0601/course_outline.htm. An example of a one-hour multisensor rainfall product for the mid Atlantic region is shown in Fig. 2.

The first step in the MPE processing is to mosaic the hourly DPA products from adjacent radars onto the national HRAP grid while taking into account any radar beam blockages that may have occurred due to local terrain. In overlapping regions of adjacent radars, the lowest-to-ground, unblocked radar estimate is used to create the mosaic so that rainfall is estimated as close to the earth's surface as possible. Rain gauge data is then incorporated in a mean, radar-wide sense to remove possible spatially-uniform biases between radar and rain gauges each hour (Seo et al. 1999) . This is necessary since WSR-88D rainrate estimates can sometimes have uniform hourly biases (e.g., overestimation by 30%) due to radar reflectivity miscalibration problems. The calibration problems are uniform across the radar and are therefore very amenable to removal through mean field bias correction. The next step is to merge the radar and rain gauge data together using geostatistical optimal estimation procedures to make local rainfall corrections based on the rain gauge data (Seo 1998). Independent satellite-based rainfall estimates produced by NOAA's National Environmental Satellite Data Information Service are then substituted in regions where radar beam blockages by terrain prevent reasonable estimation by radar alone. Additional processing capability allows computation of a local-bias-adjusted multisensor field using the rain gauge data together with the radar data (Seo and Breidenbach 2002).

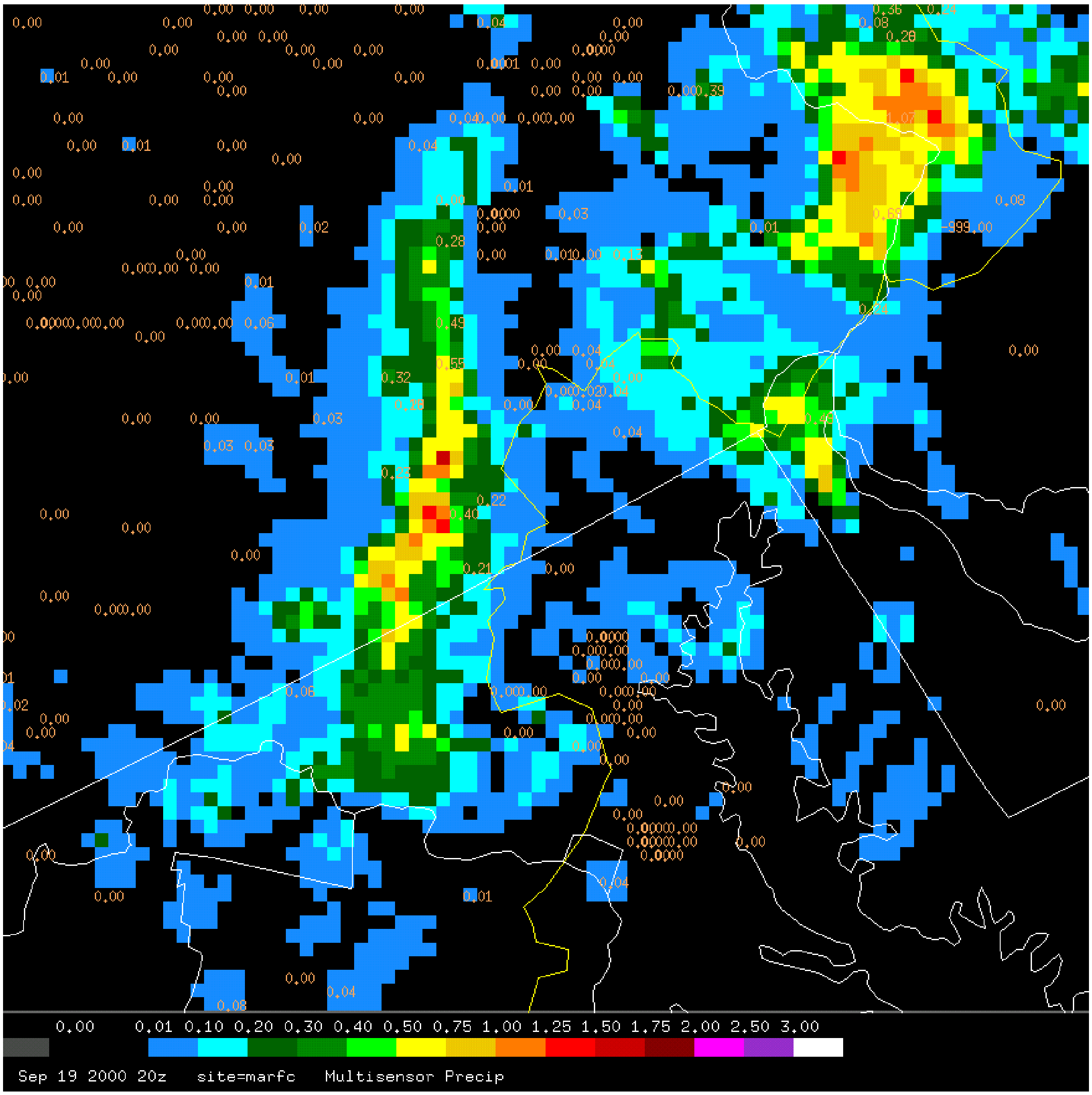

Figure 2. Example of a one-hour multisensor rainfall product over Maryland, Delaware, and southeast Pennsylvania. The grid size is approximately 4-km by 4-km.

The main objective of MPE is to reduce both spatially-mean and local bias errors in radar-derived rainfall using rain gauges and satellite so that the final multisensor rainfall product is better than any single sensor alone. The hourly regional rainfall products from the RFCs are available from most RFCs in real time. Some RFCs have more mature and timely product distribution capability than others currently. Contact each RFC directly for information on MPE product availability for their region of responsibility (see web links identified above). These MPE products are also available in non-real-time aggregated over 6- and 24-hour periods at http://www.hpc.ncep.noaa.gov/npvu/data/.

National Mosaicking

The regional hourly, quality-controlled precipitation products from each RFC are then mosaicked together nationwide by the NWS National Center for Environmental Prediction (NCEP) at a reduced resolution of 10 km. National 6- and 24-hour rainfall accumulation rainfall image products are available at http://www.hpc.ncep.noaa.gov/npvu/data/. These products are used as input to atmospheric numerical forecast models and for validation of their rainfall forecasts. An example is shown in Fig. 3.

NEW SCIENCE INFUSION ENHANCEMENTS

A 5-year science infusion plan to enhance WSR-88D precipitation estimation algorithms and products has been completed (http://www.nws.noaa.gov/oh/hrl/papers/papers.htm#wsr88d). This plan outlines the science and technology gaps that currently exist in the PPS and MPE algorithms and describes possible solutions to resolve them. A selection of some of the more significant planned enhancements is included here.

Reduce Range-related Biases

One of the biggest sources of error for rainfall estimation using radar is the degradation of rainfall estimates with increasing range due to vertical gradients in radar-observed rainrate. Because the radar beam increases in altitude with range even for very low elevation angles, the rainrate that is measured by radar at mid-far ranges (beyond 100 km or so) is sampled at higher and higher altitudes that may not necessarily be representative of the rainrate near the earth's surface. Typically the apparent rainrate as measured by radar increases from the ground level to a maximum several kilometers above the ground due to the melting of ice particles as they fall through the 0 deg C altitude and then decreases rapidly above that. This translates into rainfall estimates that can exhibit corresponding range-related biases, both positive and negative depending on the range. This problem is particularly severe in the cool seasons when the rainfall systems are shallow. A new Range Correction Algorithm has been developed that is currently being implemented within the WSR-88D computer that will correct for these biases (Seo et al. 2000). The correction factors will be computed and passed to the PPS every 5 minutes and used to correct the rainfall estimates in real time. These enhancements will be reflected in the WSR-88D rainfall products in WSR-88D software build 4 beginning in the fall of 2003.

Improve Quality Control Algorithms to Remove False Radar Returns

Rainfall can sometimes be overestimated in regions of false radar returns caused by beam ducting and ground clutter contamination. Current quality control techniques within the PPS are usually successful in removing this contamination in benign weather situations, but they have higher failure rates when the contamination exists near real rainfall echoes. The new Radar Echo Classifier (REC) is a fuzzy logic algorithm that more effectively screens out non-meteorological targets (Kessinger et al. 2001). It is currently being implemented on the WSR-88D computer and will provide more accurate delineation of raining and non-raining regions so that false radar echoes are not misidentified as rain. The use of the REC rain/no-rain products within the PPS will replace existing suboptimal quality control techniques in software build 3 in the spring of 2003.

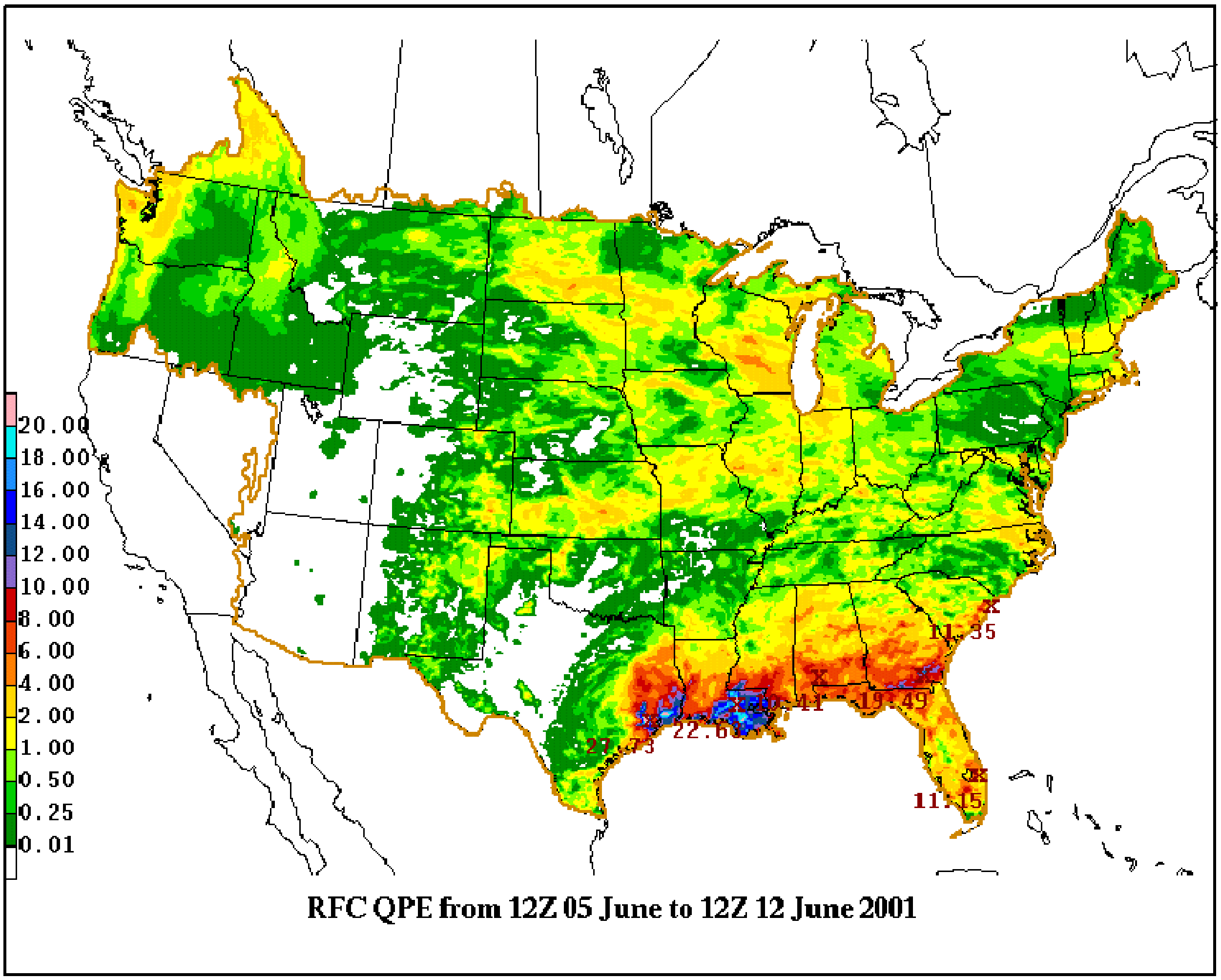

Figure 3. National mosaic of hourly MPE products from each RFC summed up for the multiday Tropical Storm Allison flooding event along the Gulf Coast.

Implement Probabilistic Radar Rainfall Techniques and Products

Current operational WSR-88D precipitation estimation algorithms such as the PPS and MPE are deterministic, i.e., they generate a single gridded rainfall field that may not necessarily be quantitatively reliable in all weather situations. Making use of independent rainfall information such as rain gauges and satellite as done currently improves the rainfall analyses, but there is no output information for users that quantifies the uncertainty in these estimates or presents them with a range of possible rainfall amounts at any given location. Current trends in operational hydrologic forecasting are moving toward probabilistic or ensemble techniques in which multiple outcomes are presented in an ensemble or probabilistic fashion so that forecast uncertainty is quantified. The same can be said for WSR-88D quantitative precipitation estimates that serve as initial conditions for hydrologic models. There is a need to develop and implement operationally viable techniques that generate not only the best estimate of rainfall up to the current time but also the possible range of values that will provide users with a measure of uncertainty to guide their cost-benefit decision making. These uncertainties in initial conditions must then be properly accounted for in ensemble-based hydrologic forecast models. The proper scientific methodology to accomplish operational probabilistic rainfall estimation is still uncertain and is an area needing further research. Funding for this activity has been identified and contractual scientific development support will begin soon.

Improve the Temporal and Spatial Resolution of WSR-88D Rainfall Products

In order to more effectively serve flash flood monitoring and forecasting needs in the NWS and externally, there is a need to increase the spatial resolution of the rainfall products. Currently the graphical PPS products are generated on a 2-km by 1-degree polar grid, and the hourly Digital Precipitation Array product used later in MPE is remapped to an even coarser 4-km by 4-km quasi-rectangular grid. There are plans to upgrade the PPS algorithm so that it produces rainfall products at the highest resolution justified by the raw radar data. Currently this is 1-km by 1-degree, but by 2006–7 the radar will begin collecting data at 0.25-km by 0.5-degree. Rainfall products at this higher resolution will improve our ability to monitor the small convective storms that often lead to flash flooding and to incorporate the rainfall product in high resolution distributed hydrologic forecast models.

Implement Polarimetric Radar Rainfall Algorithms

The current WSR-88D rainfall algorithm is based on empirical conversion of horizontally-polarized reflectivity into rainrate. Dual-polarized Doppler radars that measure both horizontally- and vertically-polarized reflectivity have existed in the research communities for several decades now, and the science of using these polarimetric radar measurements for estimating rainfall have matured enough now that this cutting-edge radar technology can be implemented on operational radars of the NWS. This will occur in the 2007 timeframe. One of the added benefits of polarimetric radar technology will be to increase the accuracy and reduce biases of radar-derived precipitation (Zrnic 1999). Additionally it has been shown to be able to delineate regions of rain vs. snow, which is important for hydrologic modeling as well as precipitation estimation, particularly in the mountains.

Enhance MPE to Provide Rainfall Products Suitable for Flash Flood Monitoring and Warning

The Multisensor Precipitation Estimator algorithm has been developed and enhanced over the past 10 years based on operational experience at the River Forecast Centers where larger-scale river forecasting is done. It more than satisfies the RFC's time and space-scale requirements for rainfall products for input into their hydrologic forecast models, i.e, 6-hourly rainfall accumulation products on the scale of the RFC river basins (100-800 mi^2). The hourly MPE rainfall products, valid at the top of the hour, at the 4-km HRAP spatial scale go well beyond the current RFC modeling requirements. However, hydrologic modeling that supports flash flood monitoring and forecasting (a Weather Forecast Office responsibility) has more stringent time and space-scale requirements for input rainfall data due to the small time and space scales associated with flash flooding. Therefore we have plans to create a new version of MPE designed specifically for the WFOs that generates multisensor rainfall products at higher time and space resolution using 5-minute radar rainfall updates from the PPS. The rainfall processing will be at a 1-km by 1-km space scale using the new WSR-88D Digital Storm-total Precipitation product described earlier as input. This scientific design activity has just begun.

Enhance MPE to Merge Satellite-based Rainfall Estimates with Radar and Rain Gauge Estimates

Satellite-based rainfall estimates provide an independent source of rainfall data that can add to existing radar and rain gauge estimates. Currently MPE makes limited use of operational satellite rainfall estimates from NESDIS in local regions defined interactively by the forecasters, such as in regions where mountain shadowing causes the radar estimates to be poor. The next step is to intimately incorporate the satellite estimates along with the radar and rain gauges over other regions. This can be accomplished by adding them as an additional estimator in the multisensor merging process in MPE that currently uses only radar and rain gauge estimators. Other techniques are being investigated such as neural network approaches.

Implement Improved Automated Rain Gauge Quality Control Procedures

High quality, real-time rain gauge data is extremely important. Reduced budgets and resulting degraded maintenance activities have caused a degradation in data quality for some rain gauge networks. Because an immediate turnaround in these trends is unlikely, improved quality assurance techniques for rain gauge data become even more important. Manual quality control of hourly rain gauge data has proven to be one of the bigger burdens to the forecasters that use MPE. Operationally available rain gauge data can be at times fraught with errors caused by inadequate maintenance, tree shielding, or clogged funnels that introduce corresponding errors in the multisensor rainfall estimates. Because of the spatial inhomogeneity of rainfall, particularly in the summer thunderstorm season, it is challenging to implement totally automated quality control procedures that don't throw out good data along with the bad data. Improved techniques that compare the gauge data with corresponding independent radar or satellite rainfall estimates are being developed for use within MPE to alleviate costly manual oversight.

CONCLUSIONS

Many improvements have been made to radar-based multisensor rainfall estimation algorithms and products since the early days of the WSR-88D nearly ten years ago. Their value as input to high resolution hydrologic forecast models has been demonstrated in recent studies and is unmatched even by very dense rain gauge networks because of the large spatial gradients of rainfall particularly in the convective summer months. These gradients are well mapped by radar and only poorly represented in rain gauge data. However, due to possible biases in radar rainfall estimates, it is clear that radar will not replace rain gauges because many well-known bias errors can appear in radar rainfall products that can be reduced significantly using high-quality, real-time rain gauge data. Some of the plans for improvements to the scientific techniques of radar rainfall estimation have been presented here. These improved techniques have been made possible through collaboration and innovation among the NWS and a diverse group of collaborating organizations and driven by the requirements defined by users of these products. The goal for the NWS is to provide our customers in the hydrologic forecasting and water management community with quantitatively reliable precipitation products that meet not only our needs but theirs as well.

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